CS162
Operating Systems and Systems Programming
Lecture 6

Synchronization: Locks and Semaphores

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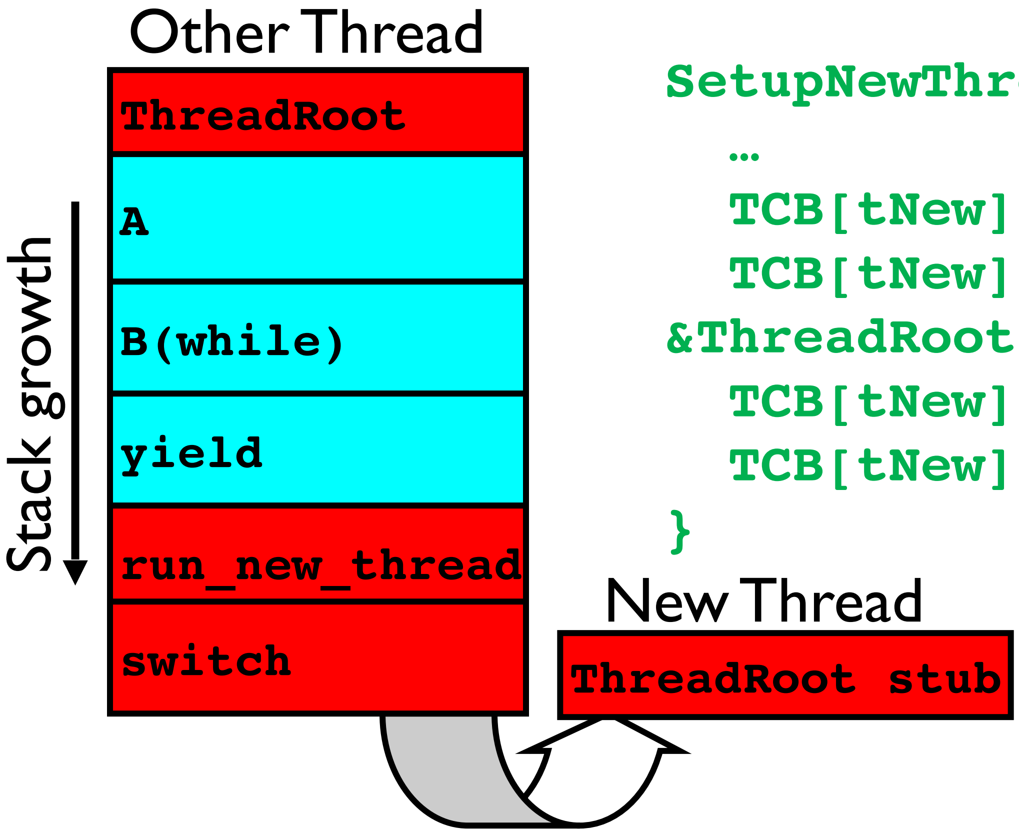
Acknowledgments: Lecture slides are from the Operating Systems course taught by John Kubiatowicz at Berkeley, with few minor updates/changes*. When slides are obtained from other sources, a reference will be noted on the bottom of that slide, in which case a full list of references is provided on the last slide.*

Recall: How does a thread get started?




```
SetupNewThread(tNew) {
  …
  TCB[tNew].regs.sp = newStackPtr;
  TCB[tNew].regs.retpc =
&ThreadRoot;
  TCB[tNew].regs.r0 = fcnPtr
  TCB[tNew].regs.r1 = fcnArgPtr
}
```

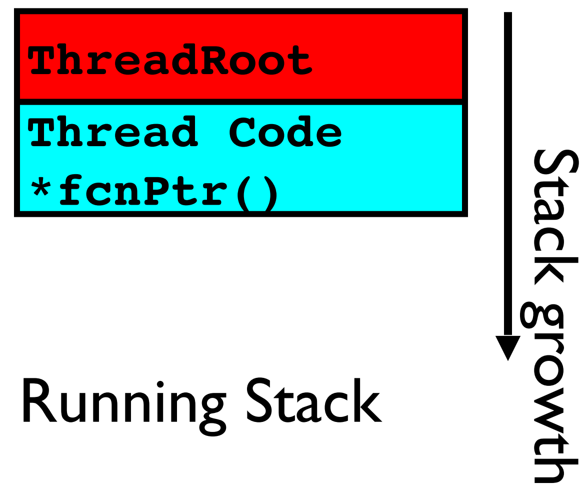
- How do we make a *new* thread?
  - Setup TCB/kernel thread to point at new user stack and ThreadRoot code
  - Put pointers to start function and args in registers
  - This depends heavily on the calling convention (i.e. RISC-V vs x86)
- Eventually, `run_new_thread()` will select this TCB and return into beginning of `ThreadRoot()`

Recall: What does `ThreadRoot()` look like?

- **`ThreadRoot()`** is the root for the thread routine:

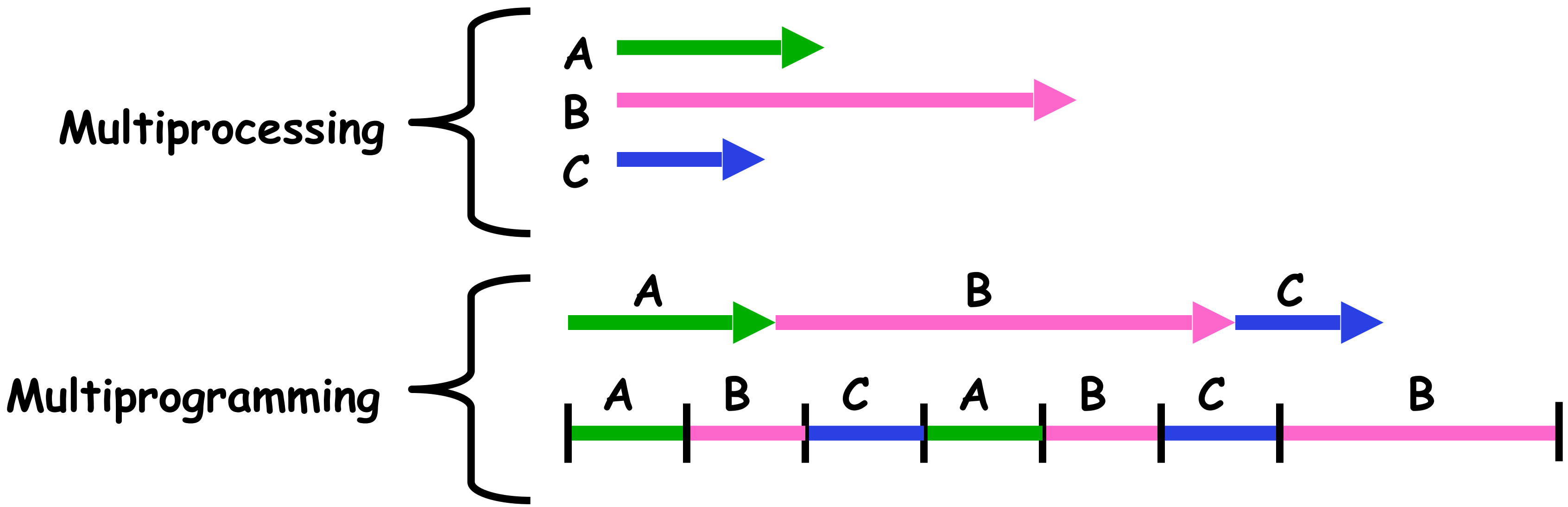
```
ThreadRoot(fcnPTR,fcnArgPtr) {
    DoStartupHousekeeping();
    UserModeSwitch(); /* enter user mode */
    Call fcnPtr(fcnArgPtr);
    ThreadFinish();
}
```

- Startup Housekeeping
  - Includes things like recording start time of thread
  - Other statistics
- Stack will grow and shrink with execution of thread
- Final return from thread returns into **`ThreadRoot()`** which calls **`ThreadFinish()`**
  - **`ThreadFinish()`** wake up sleeping threads

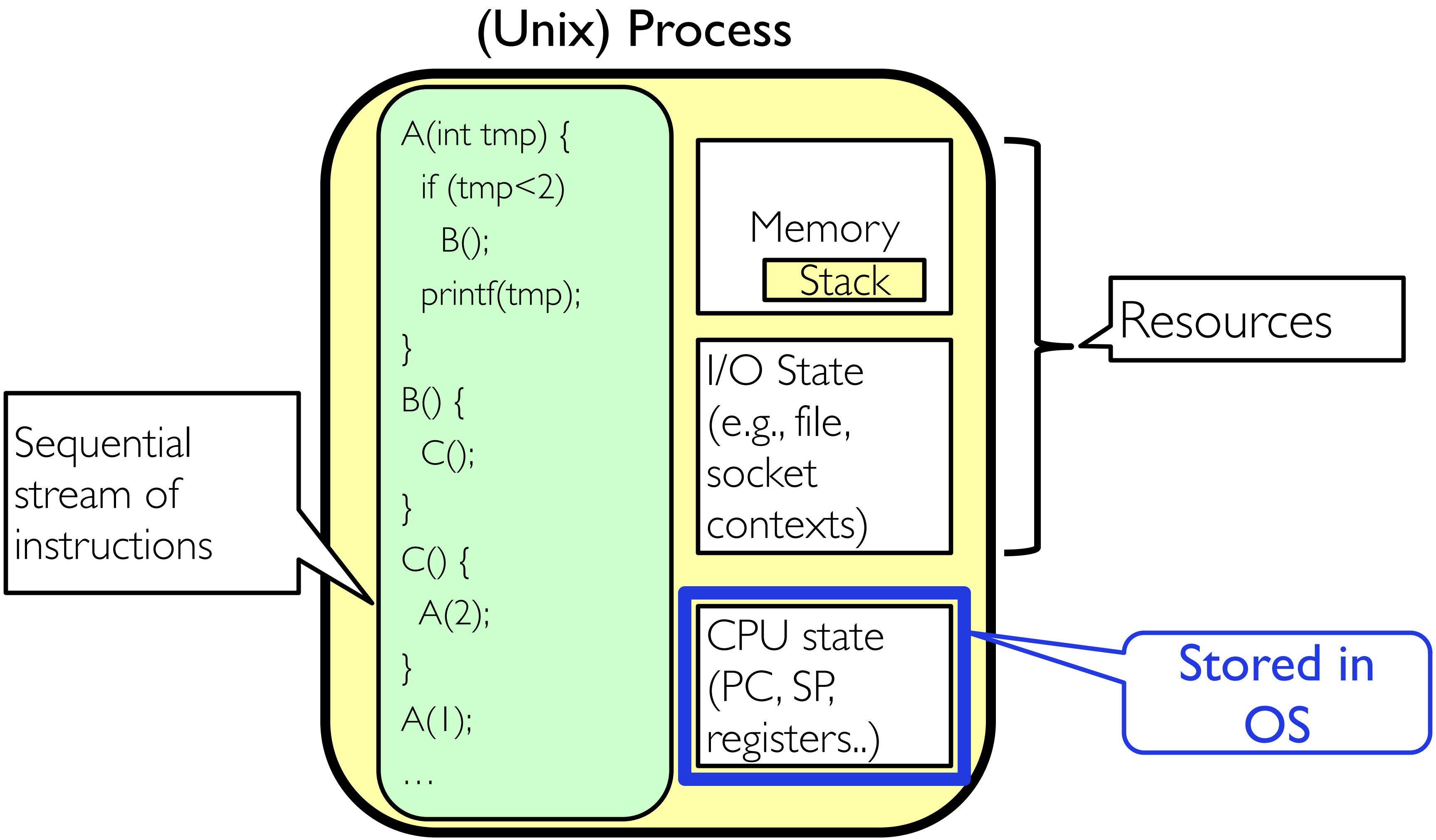


Recall: Multiprocessing vs Multiprogramming

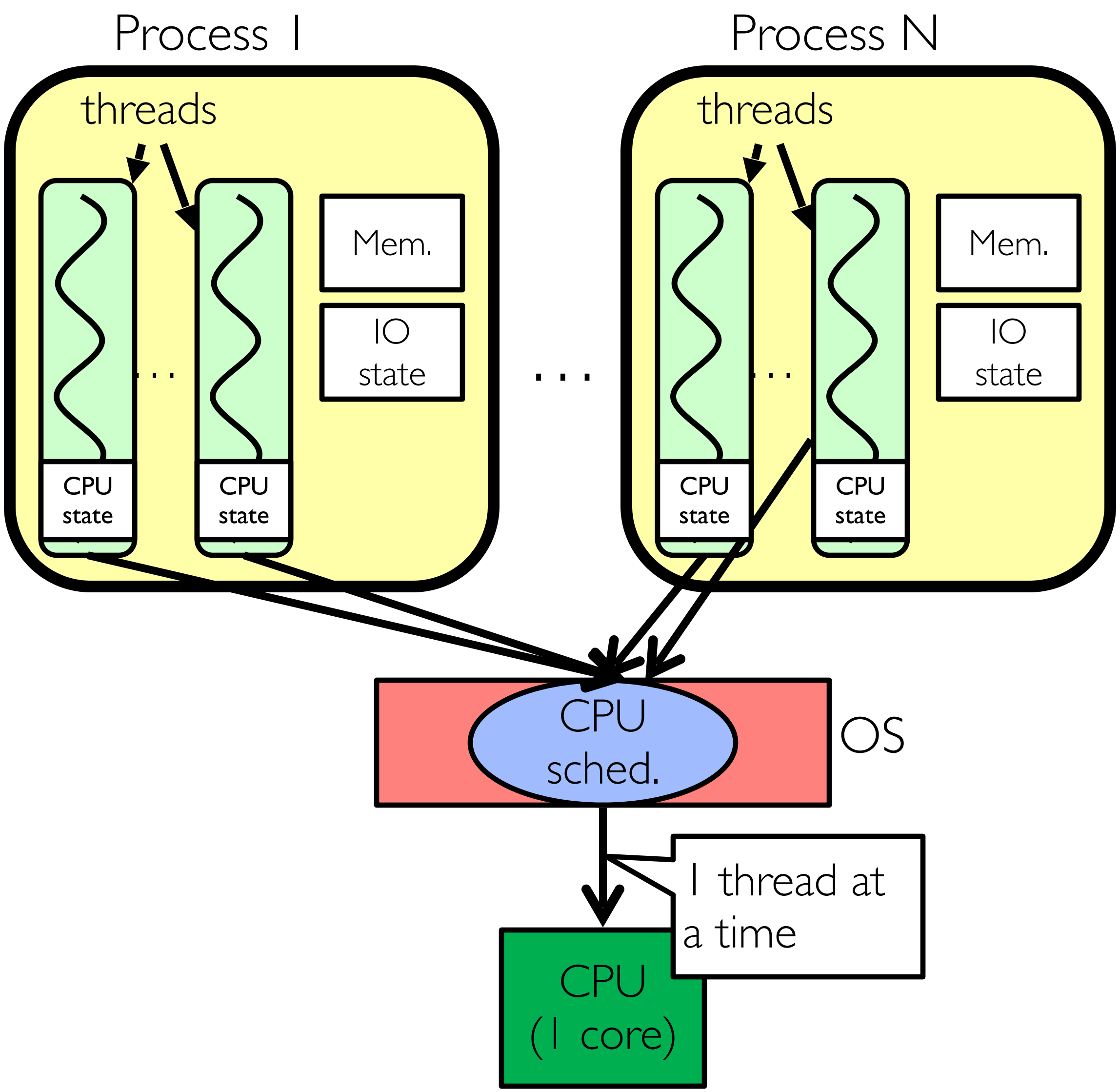
- Remember Definitions:
  - Multiprocessing ≡ Multiple CPUs
  - Multiprogramming ≡ Multiple Jobs or Processes
  - Multithreading ≡ Multiple threads per Process
- What does it mean to run two threads "concurrently"?
  - Scheduler is free to run threads in any order and interleaving: FIFO, Random, …
  - Dispatcher can choose to run each thread to completion or time-slice in big chunks or small chunks



Recall: Process

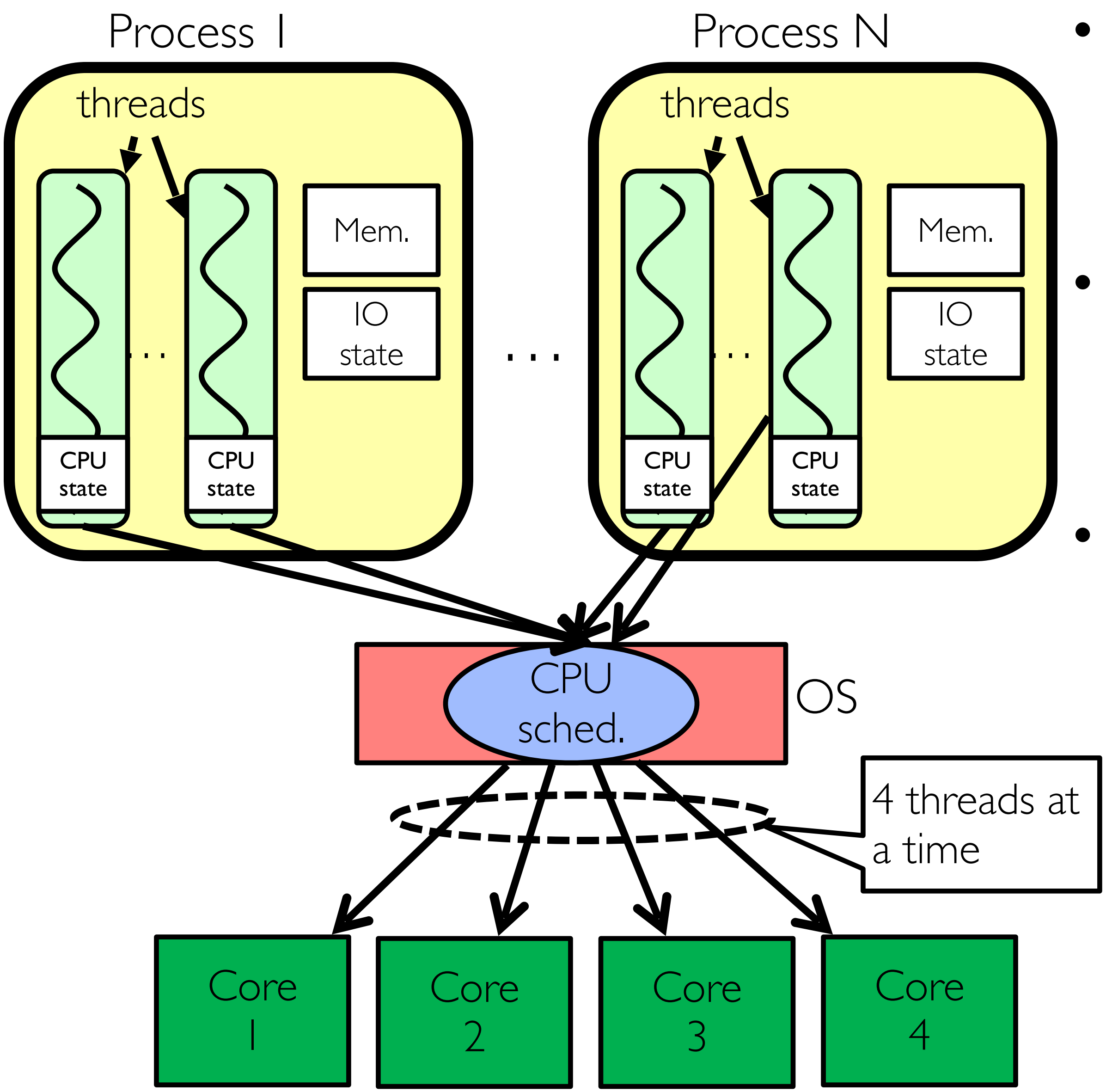


Recall: Processes vs. Threads



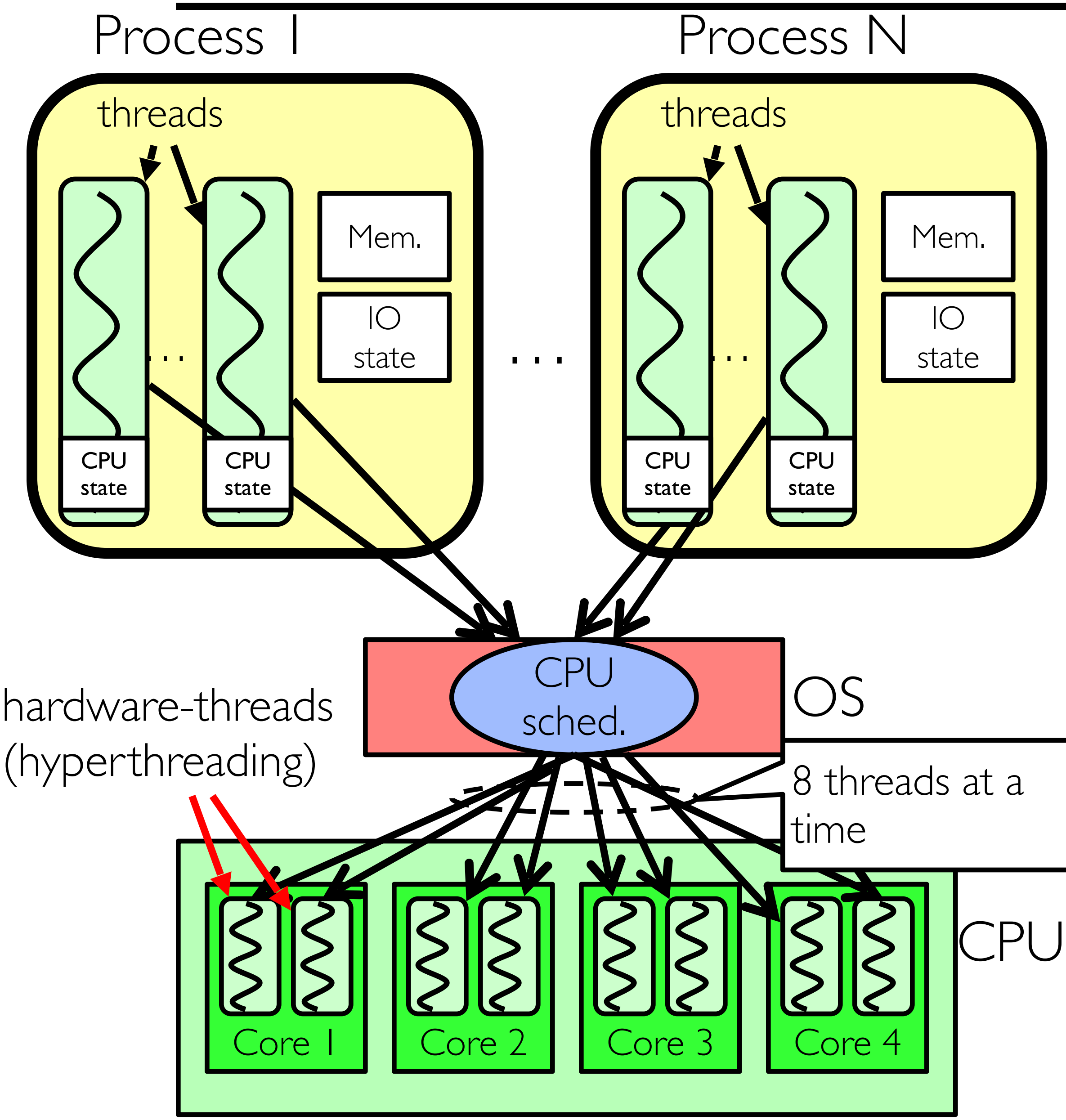
- Switch overhead:
  - Same process: low
  - Different proc.: high
- Protection
  - Same proc: low
  - Different proc: high
- Sharing overhead
  - Same proc: med
  - Different proc: high
  - Note that sharing always involves at least a context switch!

Recall: Processes vs. Threads (Multi-Core)



- Switch overhead:
  - Same process: low
  - Different proc.: med
- Protection
  - Same proc: low
  - Different proc: med
- Sharing overhead
  - Same proc: low
  - Different proc: med
  - May not need to switch at all!

Recall: Hyper-Threading



- Switch overhead between hardware-threads: ***very-low*** (done in hardware)
- Contention for ALUs/FPUs may hurt performance

Kernel versus User-Mode Threads

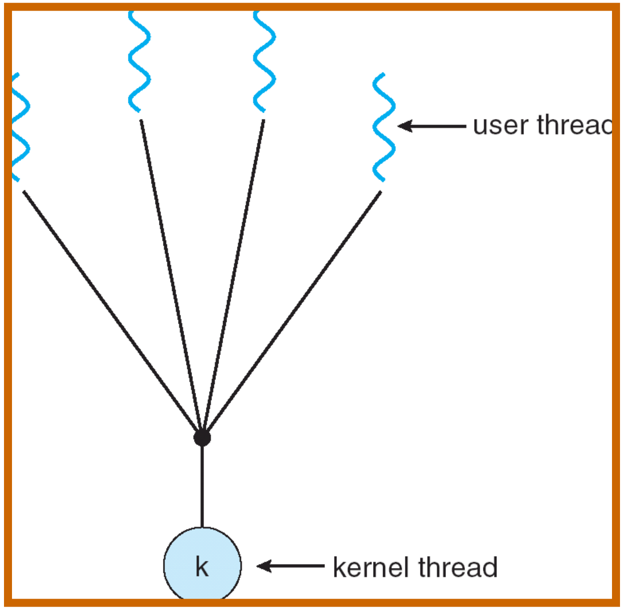
- We have been talking about kernel threads
  – Native threads supported directly by the kernel
  – Every thread can run or block independently
  – One process may have several threads waiting on different things

- Downside of kernel threads: a bit expensive
  – Need to make a crossing into kernel mode to schedule

- Lighter weight option: User level Threads

User-Mode Threads

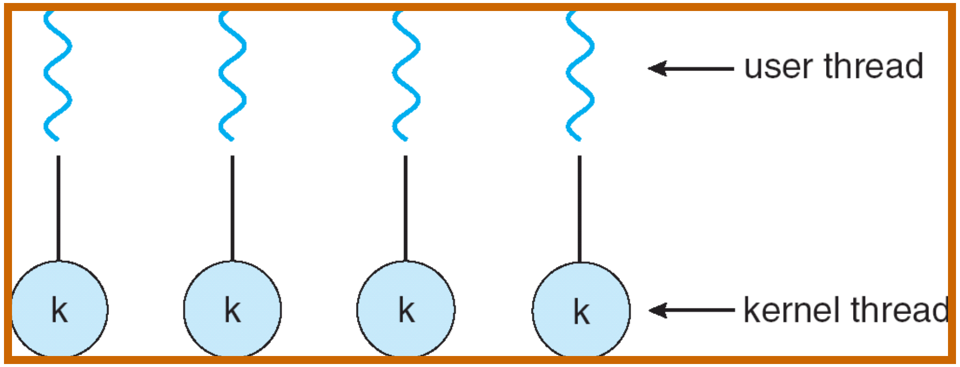
- Lighter weight option:
  - User program provides scheduler and thread package
  - May have several user threads per kernel thread
  - User threads may be scheduled non-preemptively relative to each other (only switch on yield())
  - Cheap

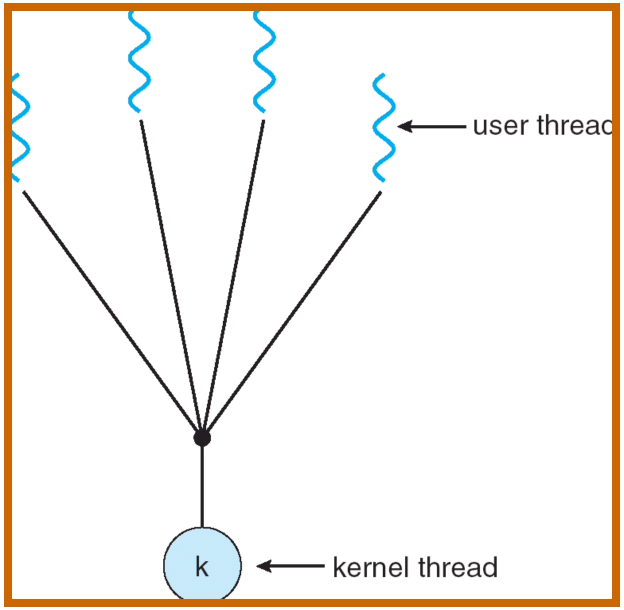


- Downside of user threads:
  - When one thread blocks on I/O, all threads block
  - Kernel cannot adjust scheduling among all threads
  - Option: *Scheduler Activations*
    - » Have kernel inform user level when thread blocks…

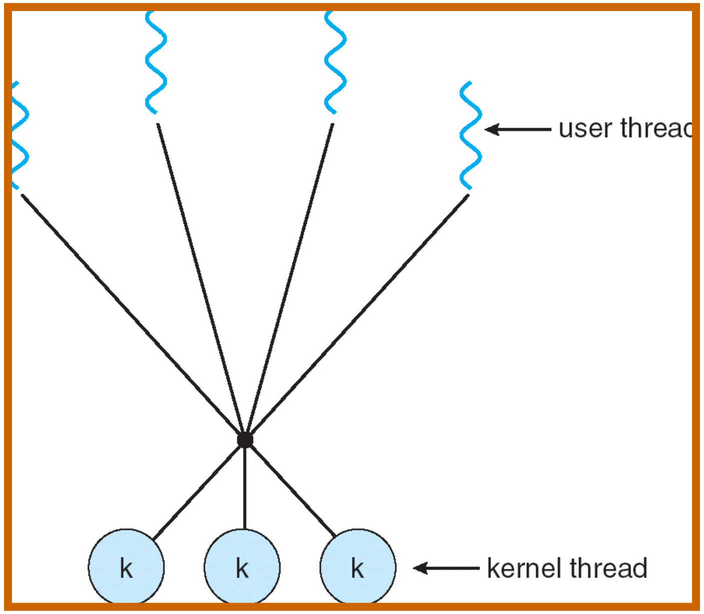
Some Threading Models

Simple One-to-One Threading Model (PINTOS!)





Many-to-One



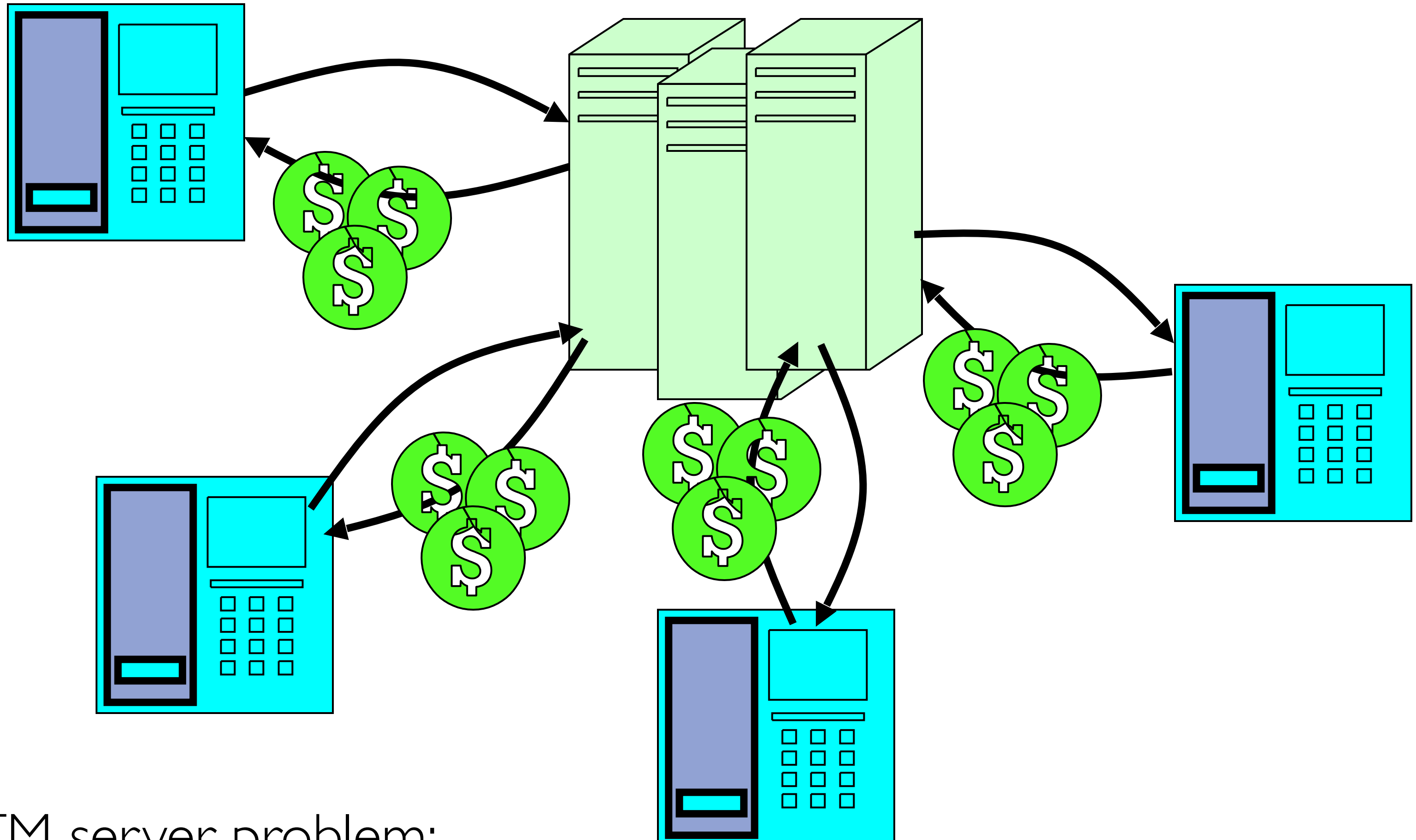
Many-to-Many

Classification

# threads Per AS: / # of addr spaces:	One	Many
One	MS/DOS, early Macintosh	Traditional UNIX
Many	Embedded systems (Geoworks, VxWorks, JavaOS,etc) JavaOS, Pilot(PC)	Mach, OS/2, Linux Windows 10 Win NT to XP, Solaris, HP-UX, OS X

- Most operating systems have either
  - One or many address spaces
  - One or many threads per address space

Recall: ATM Bank Server



- ATM server problem:
  - Service a set of requests
  - Do so without corrupting database
  - Don't hand out too much money

Recall: ATM bank server example

- Suppose we wanted to implement a server process to handle requests from an ATM network:

```
BankServer() {
   while (TRUE) {
      ReceiveRequest(&op, &acctId, &amount);
      ProcessRequest(op, acctId, amount);
   }
}
ProcessRequest(op, acctId, amount) {
   if (op == deposit) Deposit(acctId, amount);
   else if …
}
Deposit(acctId, amount) {
   acct = GetAccount(acctId); /* may use disk I/O */
   acct->balance += amount;
   StoreAccount(acct); /* Involves disk I/O */
}
```

- How could we speed this up?
  - More than one request being processed at once
  - Event driven (overlap computation and I/O)
  - Multiple threads (multi-proc, or overlap comp and I/O)

Recall: Can Threads Make This Easier?

- Threads yield overlapped I/O and computation without "deconstructing" code into non-blocking fragments
  - One thread per request
- Requests proceeds to completion, blocking as required:

```
Deposit(acctId, amount) {
  acct = GetAccount(actId);/* May use disk I/O */
  acct->balance += amount;
  StoreAccount(acct);     /* Involves disk I/O */
}
```

- Unfortunately, shared state can get corrupted:

```
        Thread 1                          Thread 2
load r1, acct->balance
                                     load r1, acct->balance
                                     add r1, amount2
                                     store r1, acct->balance
add r1, amount1
store r1, acct->balance
```

Administrivia

- Anything?

Recall: Atomic Operations

- To understand a concurrent program, we need to know what the underlying indivisible operations are!
- Atomic Operation: an operation that always runs to completion or not at all
  - It is *indivisible:* it cannot be stopped in the middle and state cannot be modified by someone else in the middle
  - Fundamental building block – if no atomic operations, then have no way for threads to work together
- On most machines, memory references and assignments (i.e. loads and stores) of words are atomic
- Many instructions are not atomic
  - Double-precision floating point store often not atomic
  - VAX and IBM 360 had an instruction to copy a whole array

Motivating Example: "Too Much Milk"

- Great thing about OS's – analogy between problems in OS and problems in real life
  - Help you understand real life problems better
  - But, computers are much stupider than people
- Example: People need to coordinate:

Time	Person A	Person B
3:00	Look in Fridge. Out of milk	
3:05	Leave for store	
3:10	Arrive at store	Look in Fridge. Out of milk
3:15	Buy milk	Leave for store
3:20	Arrive home, put milk away	Arrive at store
3:25		Buy milk
3:30		Arrive home, put milk away

Definitions

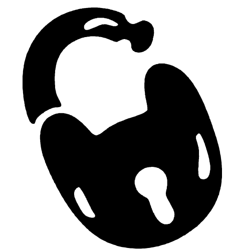
- Synchronization: using atomic operations to ensure cooperation between threads
  – For now, only loads and stores are atomic
  – We are going to show that its hard to build anything useful with only reads and writes

- Mutual Exclusion: ensuring that only one thread does a particular thing at a time
  – One thread *excludes* the other while doing its task

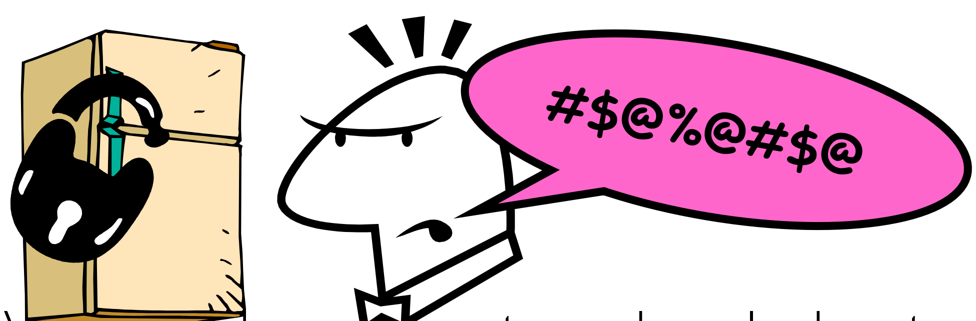
- Critical Section: piece of code that only one thread can execute at once. Only one thread at a time will get into this section of code
  – Critical section is the result of mutual exclusion
  – Critical section and mutual exclusion are two ways of describing the same thing

More Definitions

- Lock: prevents someone from doing something
  - Lock before entering critical section and before accessing shared data
  - Unlock when leaving, after accessing shared data
  - Wait if locked
    - » Important idea: all synchronization involves waiting



- For example: fix the milk problem by putting a key on the refrigerator
  - Lock it and take key if you are going to go buy milk
  - Fixes too much: roommate angry if only wants OJ



  - Of Course – We don't know how to make a lock yet

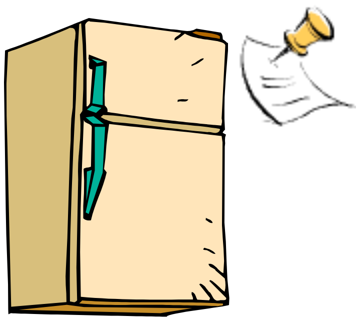
Too Much Milk: Correctness Properties

- Need to be careful about correctness of concurrent programs, since non-deterministic
  - Impulse is to start coding first, then when it doesn't work, pull hair out
  - Instead, think first, then code
  - Always write down behavior first
- What are the correctness properties for the "Too much milk" problem???
  - Never more than one person buys
  - Someone buys if needed
- Restrict ourselves to use only atomic load and store operations as building blocks

Too Much Milk: Solution #1

- Use a note to avoid buying too much milk:
  - Leave a note before buying (kind of "lock")
  - Remove note after buying (kind of "unlock")
  - Don't buy if note (wait)
- Suppose a computer tries this (remember, only memory read/write are atomic):

```
        if (noMilk) {
    if (noNote) {
        leave Note;
        buy milk;
        remove note;
    }
}
```



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  - Remove note after buying (kind of "unlock")
  - Don't buy if note (wait)
- Suppose a computer tries this (remember, only memory read/write are atomic):

Thread A

```
if (noMilk) {


   if (noNote) {
     leave Note;
      buy Milk;
      remove Note;
   }
 }
```

Thread B

```

if (noMilk) {
   if (noNote) {






      leave Note;
      buy Milk;
         remove Note;
   }
}
```

Too Much Milk: Solution #1

- Use a note to avoid buying too much milk:
  - Leave a note before buying (kind of "lock")
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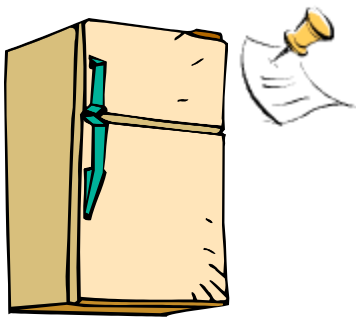
        remove note;
    }
}
```



- Result?
  - Still too much milk but only occasionally!
  - Thread can get context switched after checking milk and note but before buying milk!
- Solution makes problem worse since fails intermittently
  - Makes it really hard to debug…
  - Must work despite what the dispatcher does!

Too Much Milk: Solution #1½

- Clearly the Note is not quite blocking enough
  – Let's try to fix this by placing note first
- Another try at previous solution:

```
            leave Note;
            if (noMilk) {
         if (noNote) {
             buy milk;
         }
      }
            remove Note;
```

- What happens here?
  – Well, with human, probably nothing bad
  – With computer: no one ever buys milk

Too Much Milk Solution #2

- How about labeled notes?
  - Now we can leave note before checking
- Algorithm looks like this:

Thread A

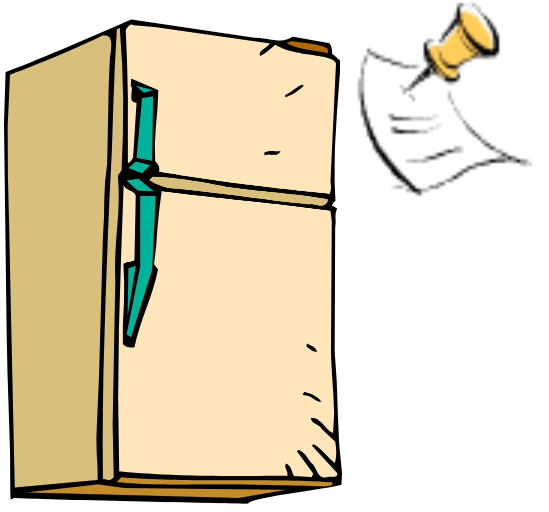
```
leave note A;
if (noNote B) {
    if (noMilk) {
        buy Milk;
    }
}
remove note A;
```

Thread B

```
leave note B;
if (noNoteA) {
    if (noMilk) {
        buy Milk;
    }
}
remove note B;
```

- Does this work?
- Possible for neither thread to buy milk
  - Context switches at exactly the wrong times can lead each to think that the other is going to buy
- Really insidious:
  - Extremely unlikely this would happen, but will at worse possible time
  - Probably something like this in UNIX

Too Much Milk Solution #2: problem!



- *I'm* not getting milk, *You're* getting milk
- This kind of lockup is called "starvation!"

Too Much Milk Solution #3

- Here is a possible two-note solution:

Thread A

```
leave note A;
while (note B) {\\X
   do nothing;
}
if (noMilk) {
   buy milk;
}
remove note A;
```

Thread B

```
leave note B;
if (noNote A) {\\Y
   if (noMilk) {
      buy milk;
   }
}
remove note B;
```

- Does this work? Yes. Both can guarantee that:
  - It is safe to buy, or
  - Other will buy, ok to quit
- At **X**:
  - If no note B, safe for A to buy,
  - Otherwise wait to find out what will happen
- At **Y**:
  - If no note A, safe for B to buy
  - Otherwise, A is either buying or waiting for B to quit

Case 1

- "`leave note A`" happens before "`if (noNote A)`"

```
leave note A;
while (note B) {\\X
    do nothing;
};
```

happened before

```
leave note B;
if (noNote A) {\\Y
    if (noMilk) {
        buy milk;
    }
}
remove note B;
```

```
if (noMilk) {
    buy milk;        }
}
remove note A;
```

Case 1

- "`leave note A`" happens before "`if (noNote A)`"

```
leave note A;
while (note B) {\\X
    do nothing;
};
```

happened before

```
leave note B;
if (noNote A) {\\Y
    if (noMilk) {
        buy milk;
    }
}
remove note B;
```

```
if (noMilk) {
    buy milk;      }
}
remove note A;
```

Case 1

- "`leave note A`" happens before "`if (noNote A)`"

```
leave note A;
while (note B) {\\X
    do nothing;
};
```

happened before

```
leave note B;
if (noNote A) {\\Y
    if (noMilk) {
        buy milk;
    }
}
remove note B;
```

Wait for note B to be removed

```
if (noMilk) {
    buy milk;
}
remove note A;
```

}

Case 2

- "`if (noNote A)`" happens before "`leave note A`"

happened before

```
leave note A;
while (note B) {\\X
    do nothing;
};

if (noMilk) {
    buy milk;        }
}
remove note A;
```

```
leave note B;
if (noNote A) {\\Y
    if (noMilk) {
        buy milk;
    }
}
remove note B;
```

Case 2

- "`if (noNote A)`" happens before "`leave note A`"

```
leave note B;
if (noNote A) {\\Y
     if (noMilk) {
          buy milk;
     }
}
remove note B;
```

happened before

```
leave note A;
while (note B) {\\X
     do nothing;
};
```

```
if (noMilk) {
     buy milk;       }
}
remove note A;
```

Case 2

- "`if (noNote A)`" happens before "`leave note A`"

```
leave note B;
if (noNote A) {\\Y
      if (noMilk) {
            buy milk;
      }
}
remove note B;
```

happened before

```
leave note A;
while (note B) {\\X
      do nothing;
};
```

Wait for note B to be removed

```
if (noMilk) {
      buy milk;      }
}
remove note A;
```

Solution #3 discussion

- Our solution protects a single "Critical-Section" piece of code for each thread:

```
if (noMilk) {
   buy milk;
}
```

- Solution #3 works, but it's really unsatisfactory
  - Really complex – even for this simple an example
    - » Hard to convince yourself that this really works
  - A's code is different from B's – what if lots of threads?
    - » Code would have to be slightly different for each thread
  - While A is waiting, it is consuming CPU time
    - » This is called "busy-waiting"
- There's a better way
  - Have hardware provide higher-level primitives than atomic load & store
  - Build even higher-level programming abstractions on this hardware support

Too Much Milk: Solution #4

- Suppose we have some sort of implementation of a lock
  - `lock.Acquire()` – wait until lock is free, then grab
  - `lock.Release()` – Unlock, waking up anyone waiting
  - These must be atomic operations – if two threads are waiting for the lock and both see it's free, only one succeeds to grab the lock
- Then, our milk problem is easy:

```
milklock.Acquire();
if (nomilk)
   buy milk;
milklock.Release();
```

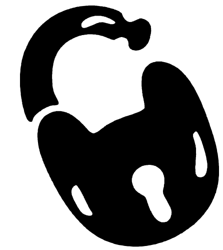
- Once again, section of code between **`Acquire()`** and **`Release()`** called a "Critical Section"

Where are we going with synchronization?

Programs	Shared Programs
Higher-level API	Locks Semaphores Monitors Send/Receive
Hardware	Load/Store Disable Ints Test&Set Compare&Swap

- We are going to implement various higher-level synchronization primitives using atomic operations
  - Everything is pretty painful if only atomic primitives are load and store
  - Need to provide primitives useful at user-level

How to Implement Locks?



- Lock: prevents someone from doing something
  - Lock before entering critical section and before accessing shared data
  - Unlock when leaving, after accessing shared data
  - Wait if locked
    - » Important idea: all synchronization involves waiting
    - » Should *sleep* if waiting for a long time
- Atomic Load/Store: get solution like Milk #3
  - Pretty complex and error prone
- Hardware Lock instruction
  - Is this a good idea?
  - What about putting a task to sleep?
    - » What is the interface between the hardware and scheduler?
  - Complexity?
    - » Done in the Intel 432
    - » Each feature makes HW more complex and slow

Naïve use of Interrupt Enable/Disable

- How can we build multi-instruction atomic operations?
  - Recall: dispatcher gets control in two ways.
    - » Internal: Thread does something to relinquish the CPU
    - » External: Interrupts cause dispatcher to take CPU
  - On a uniprocessor, can avoid context-switching by:
    - » Avoiding internal events
    - » Preventing external events by disabling interrupts
- Consequently, naïve Implementation of locks:

```
LockAcquire { disable Ints; }
    LockRelease { enable Ints; }
```

- Problems with this approach:
  - Can't let user do this! Consider following:

```
        LockAcquire();
  While(TRUE) {;}
```

  - Real-Time system—no guarantees on timing!
    - » Critical Sections might be arbitrarily long
  - What happens with I/O or other important events?
    - » "Reactor about to meltdown. Help?"

Better Implementation of Locks by Disabling Interrupts

- Key idea: maintain a lock variable and impose mutual exclusion only during operations on that variable

```
int value = FREE;
```

```
Acquire() {
   disable interrupts;
   if (value == BUSY) {
      put thread on wait queue;
      Go to sleep();
      // Enable interrupts?
   } else {
      value = BUSY;
   }
   enable interrupts;
}
```

```
Release() {
   disable interrupts;
   if (anyone on wait queue) {
      take thread off wait queue
      Place on ready queue;
   } else {
      value = FREE;
   }
   enable interrupts;
}
```

New Lock Implementation: Discussion

- Why do we need to disable interrupts at all?
  – Avoid interruption between checking and setting lock value
  – Otherwise two threads could think that they both have lock

```
Acquire() {
   disable interrupts;
   if (value == BUSY) {
      put thread on wait queue;
      Go to sleep();
      // Enable interrupts?
   } else {
      value = BUSY;
   }
   enable interrupts;
}
```

Critical Section

- Note: unlike previous solution, the critical section (inside `Acquire()`) is very short
  – User of lock can take as long as they like in their own critical section: doesn't impact global machine behavior
  – Critical interrupts taken in time!

Interrupt Re-enable in Going to Sleep

- What about re-enabling ints when going to sleep?

```
Acquire() {
   disable interrupts;
   if (value == BUSY) {
      put thread on wait queue;
      Go to sleep();
   } else {
      value = BUSY;
   }
   enable interrupts;
}
```

Interrupt Re-enable in Going to Sleep

- What about re-enabling ints when going to sleep?

Enable Position

```
Acquire() {
   disable interrupts;
   if (value == BUSY) {
      put thread on wait queue;
      Go to sleep();
   } else {
      value = BUSY;
   }
   enable interrupts;
}
```

- Before Putting thread on the wait queue?

Interrupt Re-enable in Going to Sleep

- What about re-enabling ints when going to sleep?

Enable Position

```
Acquire() {
  disable interrupts;
  if (value == BUSY) {
    put thread on wait queue;
    Go to sleep();
  } else {
    value = BUSY;
  }
  enable interrupts;
}
```

- Before Putting thread on the wait queue?
  – Release can check the queue and not wake up thread

Interrupt Re-enable in Going to Sleep

- What about re-enabling ints when going to sleep?

Enable Position

```
Acquire() {
   disable interrupts;
   if (value == BUSY) {
      put thread on wait queue;
      Go to sleep();
   } else {
      value = BUSY;
   }
   enable interrupts;
}
```

- Before Putting thread on the wait queue?
  – Release can check the queue and not wake up thread
- After putting the thread on the wait queue

Interrupt Re-enable in Going to Sleep

- What about re-enabling ints when going to sleep?

Enable Position

```
Acquire() {
   disable interrupts;
   if (value == BUSY) {
      put thread on wait queue;
      Go to sleep();
   } else {
      value = BUSY;
   }
   enable interrupts;
}
```

- Before Putting thread on the wait queue?
  – Release can check the queue and not wake up thread
- After putting the thread on the wait queue
  – Release puts the thread on the ready queue, but the thread still thinks it needs to go to sleep
  – Misses wakeup and still holds lock (deadlock!)

`

- What about re-enabling ints when going to sleep?

```
Acquire() {
   disable interrupts;
   if (value == BUSY) {
      put thread on wait queue;
      Go to sleep();
   } else {
      value = BUSY;
   }
   enable interrupts;
}
```

Enable Position

- Before Putting thread on the wait queue?
  – Release can check the queue and not wake up thread
- After putting the thread on the wait queue
  – Release puts the thread on the ready queue, but the thread still thinks it needs to go to sleep
  – Misses wakeup and still holds lock (deadlock!)
- Want to put it after **`sleep()`**. But – how?

How to Re-enable After Sleep()?

- In scheduler, since interrupts are disabled when you call sleep:
  - Responsibility of the next thread to re-enable ints
  - When the sleeping thread wakes up, returns to acquire and re-enables interrupts

<u>Thread A</u> <u>Thread B</u>

```
              .
              .
disable ints
       sleep
          context
          switch      sleep return
                       enable ints
                                 .
                                 .
                                 .
              context disable int
                            sleep
sleep return  switch
 enable ints
              .
              .
```

Atomic Read-Modify-Write Instructions

- Problems with previous solution:
  - Can’t give lock implementation to users
  - Doesn’t work well on multiprocessor
    - » Disabling interrupts on all processors requires messages and would be very time consuming
- Alternative: atomic instruction sequences
  - These instructions read a value and write a new value atomically
  - Hardware is responsible for implementing this correctly
    - » on both uniprocessors (not too hard)
    - » and multiprocessors (requires help from cache coherence protocol)
  - Unlike disabling interrupts, can be used on both uniprocessors and multiprocessors

Examples of Read-Modify-Write

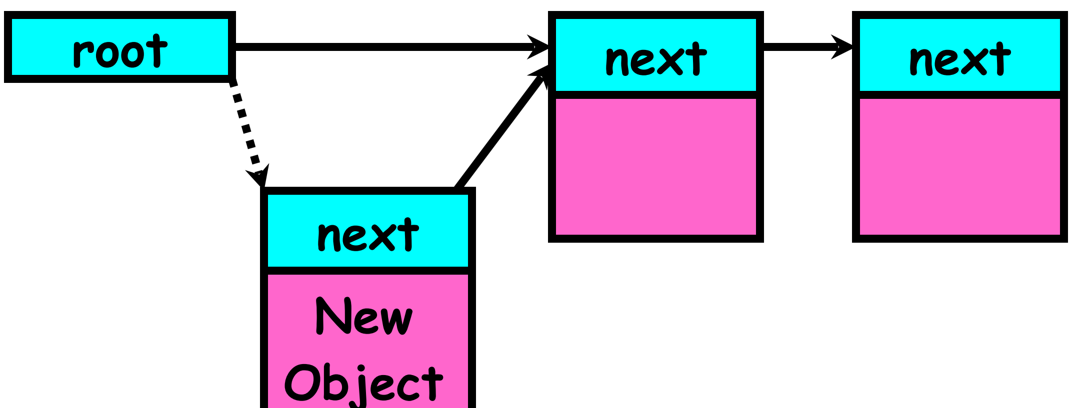
- ```
  test&set (&address) {           /* most architectures */
       result = M[address];       // return result from "address" and
       M[address] = 1;            // set value at "address" to 1
       return result;
  }
  ```
- ```
  swap (&address, register) {     /* x86 */
       temp = M[address];         // swap register's value to
       M[address] = register;     // value at "address"
       register = temp;
  }
  ```
- ```
  compare&swap (&address, reg1, reg2) { /* 68000 */
       if (reg1 == M[address]) {  // If memory still == reg1,
            M[address] = reg2;    // then  put reg2 => memory
            return success;
       } else {                   // Otherwise do not change memory
            return failure;
       }
  }
  ```
- ```
  load-linked&store-conditional(&address) { /* R4000, alpha */
       loop:
            ll r1, M[address];
            movi r2, 1;          // Can do arbitrary computation
            sc r2, M[address];
            beqz r2, loop;
  }
  ```

Using of Compare&Swap for queues

```
• compare&swap (&address, reg1, reg2) { /* 68000 */
      if (reg1 == M[address]) {
          M[address] = reg2;
          return success;
      } else {
          return failure;
      }
  }
```

Here is an atomic add to linked-list function:

```
  addToQueue(&object) {
      do {                      // repeat until no conflict
          ld r1, M[root]        // Get ptr to current head
          st r1, M[object]      // Save link in new object
      } until (compare&swap(&root,r1,object));
  }
```



Implementing Locks with test&set

- Another flawed, but simple solution:

```
int value = 0; // Free
Acquire() {
   while (test&set(value)); // while busy
}
Release() {
   value = 0;
}
```

- Simple explanation:
  – If lock is free, test&set reads 0 and sets value=1, so lock is now busy. It returns 0 so while exits.
  – If lock is busy, test&set reads 1 and sets value=1 (no change) It returns 1, so while loop continues.
  – When we set value = 0, someone else can get lock.
- Busy-Waiting: thread consumes cycles while waiting
  – For multiprocessors: every test&set() is a write, which makes value ping-pong around in cache (using lots of network BW)

Problem: Busy-Waiting for Lock

- Positives for this solution
  - Machine can receive interrupts
  - User code can use this lock
  - Works on a multiprocessor
- Negatives
  - This is very inefficient as thread will consume cycles waiting
  - Waiting thread may take cycles away from thread holding lock (no one wins!)
  - Priority Inversion: If busy-waiting thread has higher priority than thread holding lock $\Rightarrow$ no progress!
- Priority Inversion problem with original Martian rover
- For semaphores and monitors, waiting thread may wait for an arbitrary long time!
  - Thus even if busy-waiting was OK for locks, definitely not ok for other primitives
  - Homework/exam solutions should avoid busy-waiting!

Multiprocessor Spin Locks: test&test&set

- A better solution for multiprocessors:

```
int mylock = 0; // Free
Acquire() {
   do {
      while(mylock);    // Wait until might be free
   } while(test&set(&mylock)); // exit if get lock
}

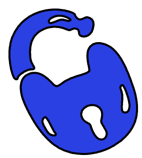
Release() {
   mylock = 0;
}
```

- Simple explanation:
  - Wait until lock might be free (only reading – stays in cache)
  - Then, try to grab lock with test&set
  - Repeat if fail to actually get lock
- Issues with this solution:
  - Busy-Waiting: thread still consumes cycles while waiting
    - » However, it does not impact other processors!

Better Locks using test&set

- Can we build test&set locks without busy-waiting?
  – Can't entirely, but can minimize!
  – Idea: only busy-wait to atomically check lock value

```
int guard = 0;
int value = FREE;
```



```
Acquire() {
   // Short busy-wait time
   while (test&set(guard));
   if (value == BUSY) {
      put thread on wait queue;
      go to sleep() & guard = 0;
   } else {
      value = BUSY;
      guard = 0;
   }
}
```

```
Release() {
   // Short busy-wait time
   while (test&set(guard));
   if anyone on wait queue {
      take thread off wait queue
      Place on ready queue;
   } else {
      value = FREE;
   }
   guard = 0;
```

- Note: sleep has to be sure to reset the guard variable
  – Why can't we do it just before or just after the sleep?

Recall: Locks using Interrupts vs. test&set

Compare to "disable interrupt" solution

```
int value = FREE;

Acquire() {
   disable interrupts;
   if (value == BUSY) {
      put thread on wait queue;
      Go to sleep();
      // Enable interrupts?
   } else {
      value = BUSY;
   }
   enable interrupts;
}
```

```
Release() {
   disable interrupts;
   if (anyone on wait queue) {
      take thread off wait queue
      Place on ready queue;
   } else {
      value = FREE;
   }
   enable interrupts;
}
```

Basically we replaced:

- `disable interrupts` → `while (test&set(guard));`
- `enable interrupts` → `guard = 0;`

Recap: Locks using interrupts

```
lock.Acquire();
 …
 critical section;
 …
lock.Release();
```

```
Acquire() {
   disable interrupts;
}
```

```
Release() {
   enable interrupts;
}
```

If one thread in critical section, no other activity (including OS) can run!

```
int value = 0;
Acquire() {
   // Short busy-wait time
   disable interrupts;
   if (value == 1) {
      put thread on wait-queue;
      go to sleep() && Enab Ints
   } else {
      value = 1;
      enable interrupts;
   }
}
```

```
Release() {
   // Short busy-wait time
   disable interrupts;
   if anyone on wait queue {
      take thread off wait-queue
      Place on ready queue;
   } else {
      value = 0;
   }
   enable interrupts;
}
```

Recap: Locks using test & set

```
lock.Acquire();
 …
 critical section;
 …
lock.Release();
```

```
int value = 0;
Acquire() {
  while(test&set(value));
}

Release() {
  value = 0;
}
```

Threads waiting to enter critical section busy-wait

```
int guard = 0;
int value = 0;
Acquire() {
  // Short busy-wait time
  while(test&set(guard));
  if (value == 1) {
    put thread on wait-queue;
    go to sleep()& guard = 0;
  } else {
    value = 1;
    guard = 0;
  }
}

Release() {
  // Short busy-wait time
  while (test&set(guard));
  if anyone on wait queue {
    take thread off wait-queue
    Place on ready queue;
  } else {
    value = 0;
  }
  guard = 0;
}
```

Higher-level Primitives than Locks

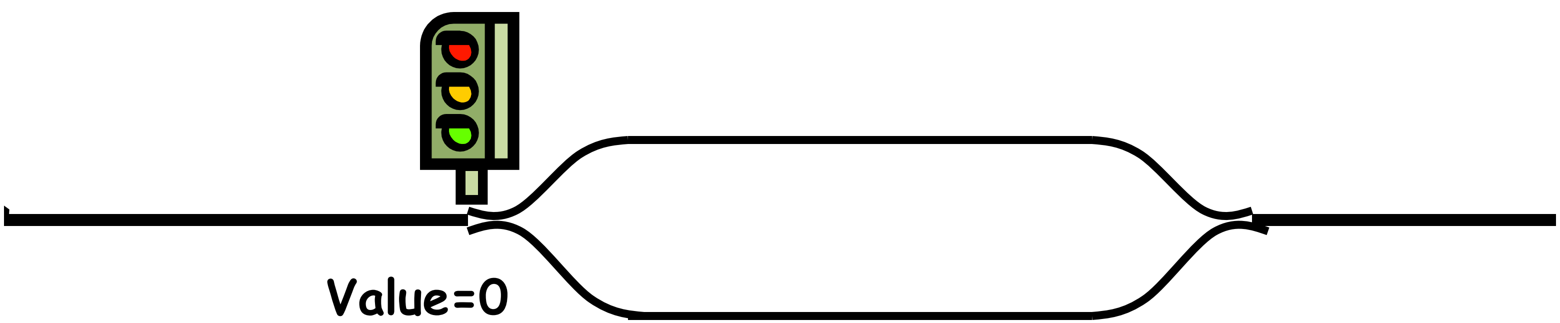
- Goal of last couple of lectures:
  - What is right abstraction for synchronizing threads that share memory?
  - Want as high a level primitive as possible
- Good primitives and practices important!
  - Since execution is not entirely sequential, really hard to find bugs, since they happen rarely
  - UNIX is pretty stable now, but up until about mid-80s (10 years after started), systems running UNIX would crash every week or so – concurrency bugs
- Synchronization is a way of coordinating multiple concurrent activities that are using shared state
  - This lecture and the next presents some ways of structured sharing

Semaphores

- Semaphores are a kind of generalized lock
  - First defined by Dijkstra in late 60s
  - Main synchronization primitive used in original UNIX
- Definition: a Semaphore has a non-negative integer value and supports the following two operations:
  - P(): an atomic operation that waits for semaphore to become positive, then decrements it by 1
    - » Think of this as the wait() operation
  - V(): an atomic operation that increments the semaphore by 1, waking up a waiting P, if any
    - » This of this as the signal() operation
  - Note that P() stands for "*proberen*" (to test) and V() stands for "*verhogen*" (to increment) in Dutch

Semaphores Like Integers Except

- Semaphores are like integers, except
  - No negative values
  - Only operations allowed are P and V – can't read or write value, except to set it initially
  - Operations must be atomic
    - » Two P's together can't decrement value below zero
    - » Similarly, thread going to sleep in P won't miss wakeup from V – even if they both happen at same time
- Semaphore from railway analogy
  - Here is a semaphore initialized to 2 for resource control:



Two Uses of Semaphores

Mutual Exclusion (initial value = 1)

- Also called "Binary Semaphore".
- Can be used for mutual exclusion:

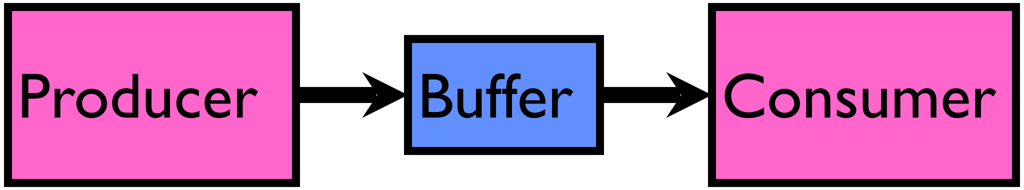
```
          semaphore.P();
// Critical section goes here
semaphore.V();
```

Scheduling Constraints (initial value = 0)

- Allow thread 1 to wait for a signal from thread 2
  - thread 2 schedules thread 1 when a given event occurs
- Example: suppose you had to implement ThreadJoin which must wait for thread to terminate:

```
Initial value of semaphore = 0
          ThreadJoin {
     semaphore.P();
}
          ThreadFinish {
     semaphore.V();
}
```

Producer-Consumer with a Bounded Buffer



- Problem Definition
  - Producer puts things into a shared buffer
  - Consumer takes them out
  - Need synchronization to coordinate producer/consumer
- Don't want producer and consumer to have to work in lockstep, so put a fixed-size buffer between them
  - Need to synchronize access to this buffer
  - Producer needs to wait if buffer is full
  - Consumer needs to wait if buffer is empty

- Example 1: GCC compiler
  - `cpp | cc1 | cc2 | as | ld`
- Example 2: Coke machine
  - Producer can put limited number of Cokes in machine
  - Consumer can't take Cokes out if machine is empty

Correctness constraints for solution

- Correctness Constraints:
  - Consumer must wait for producer to fill buffers, if none full (scheduling constraint)
  - Producer must wait for consumer to empty buffers, if all full (scheduling constraint)
  - Only one thread can manipulate buffer queue at a time (mutual exclusion)
- Remember why we need mutual exclusion
  - Because computers are stupid
  - Imagine if in real life: the delivery person is filling the machine and somebody comes up and tries to stick their money into the machine
- General rule of thumb:
  Use a separate semaphore for each constraint
  - `Semaphore fullBuffers; // consumer's constraint`
  - `Semaphore emptyBuffers;// producer's constraint`
  - `Semaphore mutex;        // mutual exclusion`

Full Solution to Bounded Buffer

```
Semaphore fullSlots = 0;   // Initially, no coke
Semaphore emptySlots = bufSize;
                           // Initially, num empty slots
Semaphore mutex = 1;       // No one using machine

Producer(item) {
    emptySlots.P();        // Wait until space
    mutex.P();             // Wait until machine free
    Enqueue(item);
    mutex.V();
    fullSlots.V();         // Tell consumers there is
                           // more coke
}
Consumer() {
    fullSlots.P();         // Check if there's a coke
    mutex.P();             // Wait until machine free
    item = Dequeue();
    mutex.V();
    emptySlots.V();        // tell producer need more
    return item;
}
```

Discussion about Solution

Decrease # of empty slots

Increase # of occupied slots

- Why asymmetry?
  - Producer does: `emptyBuffer.P(), fullBuffer.V()`
  - Consumer does: `fullBuffer.P(), emptyBuffer.V()`

Decrease # of occupied slots

Increase # of empty slots

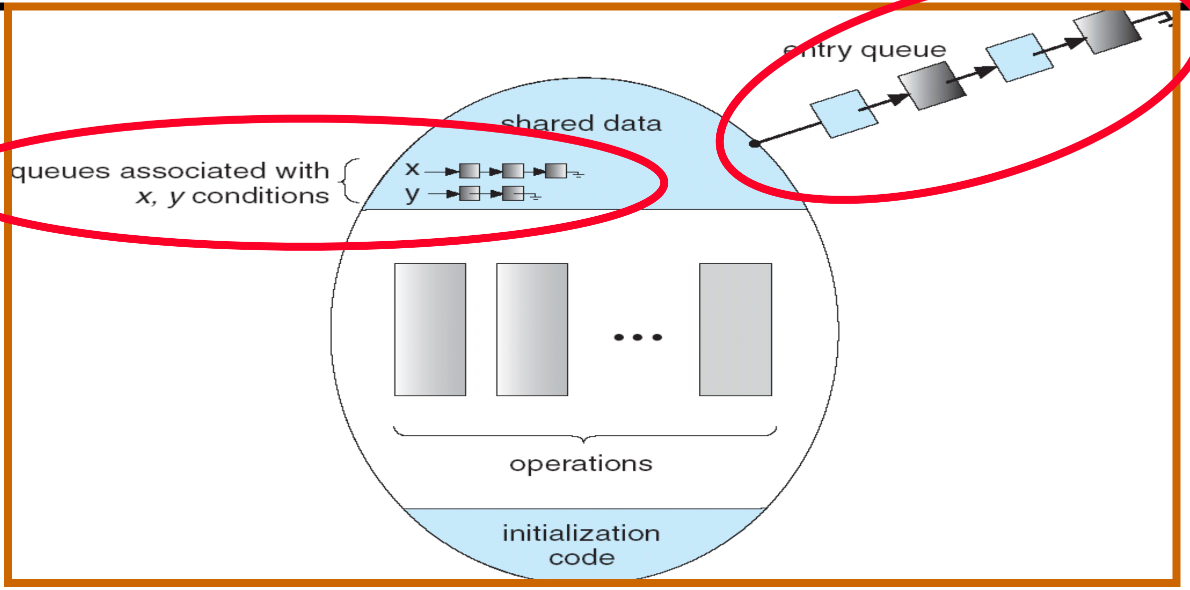
- Is order of P's important?
- Is order of V's important?
- What if we have 2 producers or 2 consumers?
  - Do we need to change anything?

```
Producer(item) {
  mutex.P();
  emptySlots.P();
  Enqueue(item);
  mutex.V();
  fullSlots.V();
}
Consumer() {
  fullSlots.P();
  mutex.P();
  item = Dequeue();
  mutex.V();
  emptySlots.V();
  return item;
}
```

Motivation for Monitors and Condition Variables

- Semaphores are a huge step up; just think of trying to do the bounded buffer with only loads and stores
  - Problem is that semaphores are dual purpose:
    - » They are used for both mutex and scheduling constraints
    - » Example: the fact that flipping of P's in bounded buffer gives deadlock is not immediately obvious. How do you prove correctness to someone?
- Cleaner idea: Use *locks* for mutual exclusion and *condition variables* for scheduling constraints
- Definition: Monitor: a lock and zero or more condition variables for managing concurrent access to shared data
  - Some languages like Java provide this natively
  - Most others use actual locks and condition variables

Monitor with Condition Variables



- Lock: the lock provides mutual exclusion to shared data
  – Always acquire before accessing shared data structure
  – Always release after finishing with shared data
  – Lock initially free
- Condition Variable: a queue of threads waiting for something *inside* a critical section
  – Key idea: make it possible to go to sleep inside critical section by atomically releasing lock at time we go to sleep
  – Contrast to semaphores: Can't wait inside critical section

Simple Monitor Example (version 1)

- Here is an (infinite) synchronized queue

```
Lock lock;
Queue queue;


AddToQueue(item) {
   lock.Acquire();            // Lock shared data
   queue.enqueue(item);       // Add item
   lock.Release();            // Release Lock
}

RemoveFromQueue() {
   lock.Acquire();            // Lock shared data
   item = queue.dequeue();// Get next item or null
   lock.Release();            // Release Lock
   return(item);              // Might return null
}
```

- Not very interesting use of "Monitor"
  – It only uses a lock with no condition variables
  – Cannot put consumer to sleep if no work!

Condition Variables

- How do we change the RemoveFromQueue() routine to wait until something is on the queue?
  - Could do this by keeping a count of the number of things on the queue (with semaphores), but error prone
- Condition Variable: a queue of threads waiting for something *inside* a critical section
  - Key idea: allow sleeping inside critical section by atomically releasing lock at time we go to sleep
  - Contrast to semaphores: Can't wait inside critical section
- Operations:
  - `Wait(&lock)`: Atomically release lock and go to sleep. Re-acquire lock later, before returning.
  - `Signal()`: Wake up one waiter, if any
  - `Broadcast()`: Wake up all waiters
- Rule: Must hold lock when doing condition variable ops!
  - In Birrell paper, he says can perform signal() outside of lock – IGNORE HIM (this is only an optimization)

Complete Monitor Example (with condition variable)

- Here is an (infinite) synchronized queue

```
Lock lock;
Condition dataready;
Queue queue;

AddToQueue(item) {
   lock.Acquire();              // Get Lock
   queue.enqueue(item);         // Add item
   dataready.signal();          // Signal any waiters
   lock.Release();              // Release Lock
}

RemoveFromQueue() {
   lock.Acquire();              // Get Lock
   while (queue.isEmpty()) {
      dataready.wait(&lock); // If nothing, sleep
   }
   item = queue.dequeue();      // Get next item
   lock.Release();              // Release Lock
   return(item);
}
```

Mesa vs. Hoare monitors

- Need to be careful about precise definition of signal and wait. Consider a piece of our dequeue code:

```
while (queue.isEmpty()) {
   dataready.wait(&lock); // If nothing, sleep
}
item = queue.dequeue(); // Get next item
```

  - Why didn't we do this?

```
if (queue.isEmpty()) {
   dataready.wait(&lock); // If nothing, sleep
}
item = queue.dequeue(); // Get next item
```

- Answer: depends on the type of scheduling
  - Hoare-style (most textbooks):
    - » Signaler gives lock, CPU to waiter; waiter runs immediately
    - » Waiter gives up lock, processor back to signaler when it exits critical section or if it waits again
  - Mesa-style (most real operating systems):
    - » Signaler keeps lock and processor
    - » Waiter placed on ready queue with no special priority
    - » Practically, need to check condition again after wait

Summary (1/2)

- Important concept: Atomic Operations
  - An operation that runs to completion or not at all
  - These are the primitives on which to construct various synchronization primitives
- Talked about hardware atomicity primitives:
  - Disabling of Interrupts, test&set, swap, compare&swap, load-locked & store-conditional
- Showed several constructions of Locks
  - Must be very careful not to waste/tie up machine resources
    - » Shouldn't disable interrupts for long
    - » Shouldn't spin wait for long
  - Key idea: Separate lock variable, use hardware mechanisms to protect modifications of that variable

Summary (2/2)

- Semaphores: Like integers with restricted interface
  - Two operations:
    - » `P()`: Wait if zero; decrement when becomes non-zero
    - » `V()`: Increment and wake a sleeping task (if exists)
    - » Can initialize value to any non-negative value
  - Use separate semaphore for each constraint
- Monitors: A lock plus one or more condition variables
  - Always acquire lock before accessing shared data
  - Use condition variables to wait inside critical section
    - » Three Operations: `Wait()`, `Signal()`, and `Broadcast()`